The Role of Pressure in the Formation of the Egersund Dolerites from SW Norway and Their Applications to Terrestrial and Martian Magmatism

A Senior Honors Thesis

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Abstract

The Egersund Dolerites intruded into southwest Norway between 600 and 700 Ma BP, in what is believed to be an extensional tectonic setting. The dikes consist of olivine tholeiites, tholeiites, and trachy basalts and are likely to have been continental flood basalt (CFB) feeder dikes. Mineralogical and chemical evidence suggest evolution at a pressure corresponding to a depth of 27-33 km with minimal fractional crystallization on ascent. This interpretation is based on a comparison of chilled margin glass and bulk rock compositions with experimental data, ratios of Al^{VI}/Al^{IV} in pyroxenes in the groundmass, a foreign gabbro rock fragment, and melt inclusions, and feldspar composition of the megacrysts, groundmass, and melt inclusions. Most continental flood basalts have undergone extensive low pressure (1 Atm) evolution before eruption, erasing chemical evidence for earlier high pressure fractionation, that occurs at the base of the crust. Low pressure evolution had little effect on the Egersund dolerite composition, and thus they represent an unique opportunity to study the early stage of evolution of CFBs. Olivine phenocrysts in the Egersund dikes contain spherical melt inclusions with an unusual Ti-rich amphibole inside called kaersutite. The occurrence of kaersutite in melt inclusions is limited to one other terrestrial cumulate, and to the SNC (shergottites, nakhlites, and the Chassigny) meteorites (presumably of Martian origin). The latter occurrence suggests that the Egersund dolerites can possibly serve as a terrestrial analog for Martian magmatism. Bulk compositions of the SNCs were plotted on the diopspside-olivine-silica triangle, and pyroxenes inside the meteorites and melt inclusions were analyzed for Al^{VI}/Al^{IV}. Bulk rock composition plots along the trend for evolution at low pressure (1 Atm), and the partitioning of Al between the VI and IV fold coordination sites suggests a low pressure of crystallization. From this, it is plausible to conclude that Martian magmatism involves large scale low pressure fractionation leading to eruption of large volumes of homogenous magma.

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Introduction

Basalts can provide a wealth of information for the geologist. The chemistry of basalts can be used to constrain the composition of the upper mantle, understand igneous processes, and reconstruct the tectonic history of a region. Basalts often originate at depths of tens of kilometers, and thus provide constraints on the composition and mineralogy of the upper mantle. Evolution of these magmas as they rise towards the surface distorts their potential as probes of the deep Earth; however, this problem can be overcome by understanding of magma evolution through the application of chemical, mineralogical, and physical models. Accurate modeling of basaltic magma evolution is essential in interpreting the data that they can provide of the processes and composition of the Earth's interior. Pressure plays a central role in magma evolution influencing the chemical and mineral composition. Thus, to accurately model the process of magma generation and evolution, the effects of pressure must be known. The Egersund Dolerites of SW Norway have the potential to provide information about processes occurring at great depths, and in order to tap this potential, their evolution must be fully understood. This paper will study the effects of pressure on the evolution of the Egersund Dolerites. The possible applications of these findings to continental flood basalts (CFBs) will also be discussed and the Egersund Dolerite's use as a terrestrial analog for the study of meteorites of presumably Martian origin.

Geology of SW Norway and the Egersund Dolerites

The geology of SW Norway is dominated by a Precambrian high-grade metamorphic complex consisting of amphibolite-granulite facies migmatites, granitic gneiss, and augen gneiss. Large anorthite to noritic plutonic bodies, smaller monzonoritic and charnockitic plutons, and two sets of basaltic dikes intrude the metamorphic complex. Around .65 Ga BP, the Egersund Dolerites crystallized in SW Norway based on Rb-Sr and Sm-Nd age dating (Miller, 1996). They strike WNW-ESE and are between .3 to 30 m wide and extend over distances as great as 60 km (Antun, 1956) (fig. 1). The exposure is generally poor, although fresh outcrops do exist usually along road cuts. The Egersund dikes crystallized at low pressure and at a fast rate based on the existence of a well defined chilled margin at the boundary between the dikes and country rock (Miller, in progress). The Egersund Dolerites have been calculated to have a volumetric flow of over km^3 per day and an ascent rate of 9 m/sec by a program utilizing physical properties and magma composition (Unkefer, 1992), which could make them possible continental flood basalt feeder dikes. The rock exposed at the surface crystallized at a depth of 3 km, and traces of large scale lava flows have been eroded (Venhuis and Barton, 1986). Field distribution, thickness, and calculated flow rates suggest that the dike system was capable of delivering vast quantities of magma to the surface, which could produce a flood basalt province.

The Egersund dike system consists of relatively fine-grained dolerites that have well defined chilled margins of glass. Venhuis and Barton (1986) classified and subdivided the Egersund dolerites based on petrography and geochemistry into olivine-tholeiites, tholeiites, and trachybasalts. In general, the rock contains phenocrysts of plagioclase, clinopyroxene, and olivine in a fine-grained matrix dominated by plagioclase and pyroxene, with some olivine and Fe-Ti oxides. The phenocrysts are euhedral with sharply defined edges suggesting no resorbtion into the melt. Spherical to irregularly shaped melt inclusions containing crystallized amphiboles, plagioclase, and clinopyroxene occur inside olivine phenocrysts , plagioclase, and pyroxene. The Egersund dolerites also contain gabbro xenoliths consisting of equal proportion of coarse grained plagioclase, clinopyroxene, and olivine. The dolerite is thought to have crystallized from an anhydrous melt with <2 Wt.% H_2O, based on the chilled margin glass composition (Barton and Miller, 1991). Major and trace element abundances are similar to ocean island basalts and hot spot-mid ocean ridge basalts, which suggests derivation from a mantle plume rather than by subduction-related processes (Miller, work in progress). As will be shown, the Egersund magma appears to have undergone extensive evolution at 8-10 kb, deep in the crust (27-33 km depth), and was transported to the surface without undergoing significant low pressure evolution that characterizes CFBs (Barton and Miller, 1991). The aim of this study is to present evidence that the Egersund dolerites underwent substantial evolution and fractional crystallization in the deep crust, unlike common flood basalts that evolve at shallow depths.

The Egersund dikes are basaltic in composition with SiO_2 contents ranging between 47.18 to 51.91 Wt. % and MgO from 4.56 to 8.06 Wt.%. Based on the total alkaline versus silica classification system, the dikes are classified as basalts and trachybasalts (Fig. 2). Silica content ranges from 47.18-51.91 Wt.% and MgO 4.56-8.06 Wt%. Major element variation between the olivine tholeiite and tholeiite are consistent with removal of augite, clinopyroxene, and olivine during fractional crystallization. The relationship with the trachy basalts is not clear but appears to involve assimilation of crustal material from a different source region (Miller, in progress).

The Role of Pressure on Mineral Chemistry

This thesis investigates the role of pressure in the evolution of the Egersund dolerites. Pressure can play an important role in the chemical evolution of a magma. For example, the composition of minerals, their relative proportion, and the make-up of the fractionating assemblage are largely influenced by pressure. Therefore, an understanding of the effects of pressure on the evolution of a basaltic magma is important if basalts are to be used as probes of the upper mantle. Several lines of evidence exist to identify and characterize the high pressure evolution of a these basaltic magmas, including the composition of the minerals, xenoliths, melt inclusions, and bulk rock.

1. The first way to study the role of pressure is by determining chilled margin glass and bulk rock compositions and comparing them to well characterized phase diagrams sensitive to the effects of pressure. Fractional crystallization involving diopside, olivine, and plagioclase can be modeled on a diopside-olivine-plagioclase-silica (Di-Ol-Pl-Sil) pseudoternary, which is a representation of the relative percentages of these four

components. The bulk composition of the chilled glasses and the basalts is plotted on a tetrahedron, with these four phases at the apexes, according to methods described by Walker Et al. (1979). Figures in this paper assume plagioclase saturation and show bulk composition in equilibrium with Di-Ol-Sil on a triangle (Fig. 3). Chilled margin glass and bulk rock composition can be compared to experimental phase boundaries and glass composition formed at pressure between 8-10 Kb on the Di-Ol-Sil triangle.

Method

The major element compositions for eight chilled margin glasses were determined in the Microprobe Lab on a Cameca SX-50 at The Ohio State University under operating conditions of 15 kv accelerating voltage, a beam current of 20 na, with a defocused spot size between 10-20 microns. Average glass compositions were determined by analyzing up to five different zones, parallel to the contact, from 50 to 3000 microns in from the contact.

Whole-rock powders were prepared and analyzed at Washington State University for major and trace elements following the methods and procedures described by Hooper et al (1993) and Knaack et al. (1994). Major element compositions were determined by X-ray fluorescence (XRF) using an automatic Rigaku 3370 spectrometer. Trace element concentrations were determined by XRF using the Rigaku 3370 and by inductively coupled plasma source mass spectrometry methods (ICP-MS) using a Sciex Elan 250 ICP-MS. Analytical uncertainties and detection limits for these methods are those determined by each lab as discussed in the references above.

Chilled Margin glasses: The chilled margin glasses represent quickly cooled magma that preserves the original melt chemistry at the time of solidification and is unmodified by in situ differentiation that might affect coarser rocks (Miller, work in progress). When plotted on the Di-Ol-Sil Pseudoternary (Fig. 3), data from experimental studies show that magmas follow a specific path for low pressures (around 1 Atm.) and plot in a different zone from those crystallizing under high pressure conditions (8-10 kb). At low pressures magmas evolve towards a more siliceous composition, whereas at higher pressures (8-10 Kb) these same magmas evolve towards silica depletion, becoming alkaline. The pressure of magma evolution can be estimated by looking at which path chilled margin samples plot.

Bulk Composition: The bulk rock composition of the dolerites can also be compared to experimental glass data at 1 atmosphere and high pressure to determine the role of pressure in the evolution of the magma. The bulk rock compositions of the Olivine tholeiites and tholeiites were plotted on the Di-Ol-Sil pseudoternary using similar methods to those for the chilled margin glasses (Fig. 4).

Results

Within the tetrahedron, the chilled margin glass samples in the Ol-Sil-Di-Pl system appear to plot in the high pressure 8-10 kb zone (fig. 4). The liquid from which they formed appears to have evolved along high pressure phase boundaries. Bulk rock compositions fall within the zone associated with high pressure, representing evolution towards decreasing silica content. This agrees with the data from the chilled margins of the dikes, which suggest that the magma evolution at high pressures dominated the chemistry of the Egersund Dolerites.

2: Another way to determine the role of pressure in magma evolution is to look at the coordination number of aluminum in clinopyroxene. The general formula for clinopyroxene can be stated as $(M2)(M1^{VI})(T^{IV})_2 O_6$. The distribution between the of Al between the M1-octahedral and tetrahedral sites in pyroxenes is pressure-dependent. At higher pressures Al substitutes more readily into the M1- octahedrally coordinated site (Thompson, 1974). Thus, minerals forming at higher pressures will have greater Al^{VI}/Al^{IV} ratios and is illustrated using experimental data in fig. 5. Bulk-magma composition and temperature also influence the partitioning of Al between the octahedral- tetrahedral sites with absolute values being specific to each magma. A general trend towards higher ratios with increasing pressure of formation, is however discernible (Wass, 1979).

This property of Al can be applied to study the role of pressure in the evolution of the Egersund Dolerites. The amount of Al in the M1 and T sites in pyroxenes contained in the groundmass, a gabbro xenolith, and melt inclusions was calculated to six oxygens and the data has been plotted on fig. 6. With lines drawn to represent the ratios 1:1, 1:2, and 1:4.

Ground Mass: As shown in figure 6, pyroxenes in the ground mass (bulk rock) consistently plot with low Al^{VI}/Al^{IV} values. The scatter most likely represents compositional zoning related to rapid cooling (Miller, work in progress). It is clear even from the scatter that the vast majority of data plot within the 1 Atm low pressure zone for experimental data and below the 1:4 ratio line. This suggests low pressure for crystallization for groundmass clinopyroxene, which is consistent with the proposed model for low pressure final crystallization of the magma (Barton and Miller, 1991).

Gabbro Xenolith: Pyroxenes inside the gabbro xenolith plot with greater Al^{VI}/Al^{IV} ratios than that for the groundmass. Their amount of total Al in either coordination is less, but the data falls on or above the 1:2 ratio line. The data is much less scattered and surprisingly coherent. The higher ratios of pyroxenes in the xenolith appears to suggest a relatively higher pressure of formation.

Melt inclusions: Melt inclusions are interpreted as liquid trapped by growing phenocrysts in igneous rock bodies. Most inclusions likely began as trapped melt in irregularities on the host crystal's growing surface (Treiman, 1992). After entrapment the inclusions may crystallize at a variety of possible cooling rates as closed systems, that only interact with the host crystal (Watson, 1976). Because the melt inclusion is separated from the melt and only reacts with its host, they may represent chemical samples of the overall melt at time of entrapment. Thus, melt inclusions can be a useful tool in retrieving magma compositions from various stages of magma evolution and often the crystallized phases they contain may be used as a tool in studying the temperature and pressure conditions of crystallization for the phenocryst. Not every inclusion can be considered to represent the original parent magma at time of host crystallization. Small inclusions (less than 25 microns) can sample the fluid composition at the crystal melt interface and give exotic compositions (Treiman, 1992). It is also possible that the entrapped melt could undergo alteration through the host crystal. Further, reaction may occur between the host crystal and the trapped melt. Whereas, generalizations can be made for interaction between the host and melt, the previous reasons necessitate care in selecting inclusions for analysis.

Melt inclusions inside the Egersund Dolerites occur in plagioclase and olivine phenocrysts, but only those in olivine were studied. The melt inclusions are partially crystallized and contain plagioclase, clinopyroxene, and an unusual amphibole, kaersutite, set in a cryptocrystalline groundmass. The grains inside the inclusion are euhedral and show no evidence of reaction with the host olivine crystal. The euhedral nature of the melt inclusions crystals suggests a slow cooling rate for these inclusions, at least for part of its history, and implies that the phenocrysts formed during evolution at some depth in the crust. Clinopyroxenes in the melt inclusions contain higher concentrations of Al (fig. 6) Al^{VI}/Al^{IV} ratios cluster around the 1:2 ratio line and all are above the 1:4 line. This suggests a higher pressure of formation than the ground mass and possibly a similar pressure of formation to the gabbro xenolith.

3. Another way to determine the role pressure plays in magma evolution is to examine the compositional zoning of plagioclase megacrysts. The relative percent of albite and anorthite in plagioclase is influenced by the pressure, temperature, water content, and bulk composition of the magma. Experiments have shown that when all other variables remain constant, increasing albite content is associated with increasing pressure. Figure 7 illustrates how the composition of Ca-feldspar changes with pressure and clearly shows the trend towards a greater sodic composition with increasing pressure. Magma differentiation is also correlated with increasing albite content. Crystals formed through normal one-stage crystallization will become more sodic as one goes from the core towards the rim due to the effects of evolving magma composition during crystal growth. Occasionally, crystals are

reversely zoned, displaying the opposite trend. Reversed zoning indicates a multi-stage evolution history involving polybaric conditions and/or magma mixing (Miller, work in progress).

The Plagioclase megacrysts in the Egersund Dolerite display reverse zoning. Figure 8 shows the more sodic nature of several plagioclase phenocrysts cores in relation to their rims. The relationship between pressure and plagioclase content was determined through regression analysis of estimates of experimental data. These equations were used to calculate the pressure for Egersund megacrysts as a function of composition. This is illustrated in figure 8, where respective core and rim compositions indicate polybaric evolution. The results point towards an initial high pressure crystal formation for the cores followed by crystallization of the rims at lower pressure.

Another insight that plagioclase composition can provide about the role of pressure in the Egersund Dolerites evolution concerns the composition of melt inclusion and groundmass feldspar. Figure 9 shows that plagioclase in the ground mass is much more Ca- enriched than the feldspar in the melt inclusion. The sodic plagioclase in the melt inclusions formed around the time its phenocrysts were forming, whereas the Ca-enriched ground mass is thought to have formed in the final stages of crystallization close to the surface. The removal of Ca by pyroxene in the inclusion could also be contributing its sodic nature of the feldspar, but the results as well as the Al coordination number data for melt inclusion pyroxenes and megacryst zoning characteristics support this interpretation. The results indicate that the plagioclase in the melt inclusions crystallized at substantially higher pressures than those in the groundmass, possibly between 8-12 kb.

Discussion

A few conclusions about their evolution can be drawn from this study of the possible effects of pressure on the chemistry and mineralogy of the Egersund Dolerites. The magma appears to have undergone extensive fractional crystallization at high pressures 8-13 kb based on three criteria.

1. The chilled margin glasses of the dolerite, which can be taken to represent the magma composition, falls along the trend for evolution at high pressure in the Ol-Di-Pl-Sil system, and overlaps with the field for experimental glasses in equilibrium with Cpx., Ol., and Plag. The trend represents a decrease in silica content toward sub-alkaline to alkaline composition with fractionation. This is opposite to the trend in liquid composition during fractionation at low pressures which shows an increase in silica content. The bulk composition of the igneous rock also falls along the 8-10kb cotectic.

2. The greater ratio of Al^{VI}/Al^{IV} in clinopyroxene (Cpx) in the melt inclusions relative to those in the ground mass indicates formation at high pressures. Most of the Cpx in the melt inclusions plot around the 1:2 ratio line and all are above the 1:4 line that separates the Cpx in the ground mass. The data suggests that the melt inclusion Cpx crystallized at similar pressures to those in the gabbro xenolith and imply that substantial fractional crystallization occurred at great depths in the crust.

3. The reverse zoning in plagioclase phenocrysts and the sodic nature of the feldspar in melt inclusions indicates polybaric evolution. Through comparison with experimental data the fact that core compositions of Ca-feldspar phenocrysts are Na-rich compared to the rims suggests initial crystallization around 10 kb and that later growth occurred at lessor pressures. The more sodic nature of feldspar in melt inclusions compared to those in the groundmass agrees with Al coordination evidence in Cpx for evolution at high pressures and final crystallization at lower pressures.

The general model for evolution of the Egersund dolerites can be summarized as 1. high pressure fractional crystallization, 2. minimal crystallization at lower pressures on the way to the surface, 3. and final low pressure crystallization at 3 km depth (<1 kb).

The Implication for Continental Flood Basalt (CFB) Genesis and Evolution

Analysis of the Egersund Dolerites provides insight into the formation and evolution of continental flood basalts. The most widely accepted model for CFB magma genesis is that magma is generated in the upper mantle by melting related to mantle thermal anomalies. Cox (1980) argued for a picrite source magma that ponds at the base of the crust and undergoes fractional crystallization until its density is low enough to rise. After rising to the upper crust the magma appears to undergo more fractional crystallization. This is based on the fact that bulk compositions of CFBs plot along the low pressure (1 Atm) cotectic in the PL-Di-Ol-Sil system shown in Figure 10 (Walker et al. 1979). This model accounts for the relatively evolved nature of CFBs and can be described as removal of olivine, plagioclase, and clinopyroxene. Fractionation at low pressures usually obliterates almost all of the evidence of high pressure evolution . Despite this, many CFBs preserve some chemical and/or mineralogical evidence for high pressure (8-10 kb) evolution (Barton and Miller, 1991). Based on this evidence the majority of CFBs appear to undergo polybaric fractionation with high pressure evolution at the base of the crust, followed by low pressure fractional crystallization before eruption.

The low pressure evolution of CFBs is well understood, but to gain a complete model of the formation and evolution of these magmas, our knowledge must be increased concerning the high pressure stages of the system. Here, the Egersund Dolerites can provide information, because they appear to have not undergone significant low pressure evolution. Bulk rock and chilled margin compositions as previously stated fall along the high pressure (8-10 kb) trend for fractionation in the Di-Ol-Pl-Sil system. The crystals in the melt inclusions likely crystallized during the high pressure stage of evolution, meaning these inclusions can be taken as samples of the magma during this stage. Therefore, several lines of physical evidence suggest that the Egersund Dolerites evolved at high pressure. Based on experimental studies and the distribution of the Egersund data in the Ol-Di-Sil triangle, it is clear that basaltic magma crystallizing at the base of the crust will evolve toward silica undersaturation, which is in contrast to the low pressure trend toward silica saturation.

There are, therefore, several implications regarding high pressure crystallization of a basaltic magma. First, because only a fraction of the melt generated in the upper mantle reaches the surface, the composition of the lower crust may be substantially modified by addition of alkaline intrusive bodies. Second, with an understanding of high pressure evolutionary processes, it may be possible to back-calculate and correct magma compositions to effectively look past low and high pressure processes. This would enable wider use of basalts for interpreting upper mantle properties. Third, the presence of a fractionating basaltic magma at the base of the crust can provide a heat source to drive metamorphic reactions. Combined with crystallization of the magma and the associated thermal input, rift zone magmatism is a possible mechanism for crustal growth and granulite facies metamorphism. Finally, a wide range of magma compositions are erupted in intraplate and rift zone settings. Fractionation provides another mechanism by which a range of magma compositions can be generated.

Future work could involve calculation of the melt composition at time of entrapment by analyzing the melt inclusions. Determinations of the melt chemistry can be done if chemical equilibrium and growth of host mineral are corrected for (Treiman, 1992). The overall composition of the inclusion must first be calculated. In the case of quick cooling of the entrapped melt, a homogeneous glass will be produced whose overall composition can be determined by point analysis with a microprobe. In the case of a slower cooling rate, the inclusion will differentiate making a bulk composition more difficult to determine accurately. The average composition of the whole grain must be determined by a wide beam or integration of a number of points. After the bulk composition of the entrapped melt is calculated it can represent (or after modification represent) the original parent magma. If little interaction has taken place between the inclusion and the host, the bulk composition of the inclusion can be considered an approximate representation of the parent melt. In most cases though, the extent of interaction that has taken place with the host mineral must be determined. This can be done in the case of olivine by adding it back in the melt using methods involving MgO/FeO ratios (Treiman, 1992). This is a logical next step that will provide a good estimate of the magma composition at the time of high pressure fractionation.

Analog for Martian Magmatism

The melt inclusions in olivine phenocrysts contain an unusual amphibole called kaersutite, that is also found in melt inclusions in what are presumably Martian meteorites, the shergottites, nakhlites, and the Chassigny (SNCs). Kaersutite is found most commonly as megacrysts and phenocrysts in alkaline basalts, veins, and crystals in mantle xenoliths; rarely, is it found associated with tholeiitic magmas. The only other known occurrence of kaersutite in melt inclusions is in the SNCs and in one terrestrial cumulate. The composition of kaersutites in the Egersund Dolerite melt inclusions, SNC melt inclusions, and other terrestrial occurrences are plotted in fig. 11. Melt inclusions in the SNCs also contain augite. The similarity between the kaersutite in the Egersund melt inclusions with those in the SNCs suggests that it might be possible to draw some parallels between the Egersund dolerite evolution and that of the SNCs.

The SNCs consist of three categories of meteorites, the Shergottites, the Nakhlites, and the Chassigny meteorite. The Shergottites and the Chassigny meteorite contain the hydrous amphibole kaersutite (McSween, 1985). The Shergottites are diabases and consist mostly of clinopyroxenes and maskelynite (a diapetic glass of plagioclase composition). The Chassigny meteorite is a dunite dominated by olivine (Fo 32) with augite and orthopyroxene. Shergottites contain trapped grains of kaersutite in pyroxene, and the Chassigny also contains trapped grains of this hydrous amphibole in olivine. McSween (1985) argues for crystallization at low pressure and a hydrous parent magma based on the presence of kaersutite, a hydrous amphibole.

My study of the Egersund Dolerites allows me to draw some conclusions about magmatic processes on Mars that could have formed these meteorites. First, The presence of kaersutite does not necessarily mean that the source magmas were hydrous. Barton and

Miller (1991) state that the Egersund Dolerites crystallized from magmas with <2% wt H_2O. The presence of kaersutite in a relatively anhydrous rock means that a hydrous magma is not necessary for formation of a hydrous amphibole. Second, the clinopyroxene Al^{VI}/Al^{IV} distribution for the melt inclusions in SNCs suggest lower pressure of crystallization than melt inclusions and xenoliths in the Egersund dolerites (Fig. 12). Third, the calculated melt composition when plotted on the Di-Ol-Sil triangle fall along the low pressure trend suggesting evolution at shallow depths. Fig. 13 shows that the SNC bulk rock composition plot around the 1 Atm. cotectic. There is much uncertainty in bulk melt compositions, but what is clear is that they do not fall along the trend for high pressure.

From these conclusions, some plausible models for Martian magmatism can be offered. The similarities in mineralogy and chemistry between the SNCs and terrestrial igneous rocks suggest that magma evolution processes similar to those on Earth occur on Mars. Melt inclusions containing kaersutites are found inside mineral grains in coarse cumulates. The mineral grains inside the melt inclusions are not quenched and are euhedral implying a slow cooling rate. It is possible that these coarse grained cumulates represent crystallization inside a magma chamber near its floor. The evidence for low-pressure evolution suggests that the magma chambers, where this final crystallization took place, were at shallow depths in the Martian crust. The fact that evidence for low pressure evolution exists in many of the SNCs implies that in the past low-pressure evolution dominated Martian magmatism. Extensive low pressure evolution of magma would produce large volumes of relatively homogenous magma similar to terrestrial CFBs and it is plausible that this might be the nature of the large volcanic plateaus on Mars.

Conclusion

This study has concluded that the Egersund Dolerites evolved at elevated pressure with final crystallization at low pressure. The Egersund dolerites can be used to study the role of magma evolution in the formation of CFBs and the SNC meteorites. Conclusions drawn from this study imply that low pressure evolution and crystallization played a role in the formation of the SNCs, and that processes in shallow magma chambers might be an important aspect of Martian magmatism. The Egersund Dolerites also have great potential in studying processes behind CFB formation, specifically the effects of high pressure evolution. Future work could involve calculating the composition of the melt at the time of entrapment in the melt inclusions. A full understanding of the processes behind the Egersund Dolerites has great application in studying terrestrial and ex-terrestrial magmatism.

References

Antun, P., 1956. Gèologie et pètrologie des dolèrites de le règion d'Egersund (Norvège Mèridonale). Ph.D. thesis (unpublished), Universitè de Liège.

Barton, M. and Miller, C.A., 1991. The Egersund dikes, SW Norway: An example of high-pressure crystalization of tholeiites. NSF proposal.

Cox, K. 1980. A model for flood basalt vulcanism. J. Petrol.,21, 629-650.

McSween, H.Y., 1985. SNC meteorites: clues to Martian petrologic evolution?. Review of Geophysics, 23 No.4, 391-416.

Miller, C.A. and Barton,M., 1996. New age and isotopic data for the Egersund Dolerites, SW Norway: evidence for Iapetus plume-initiated rifting during the late Precambrian. Abstract, AGU spring meeting, 277.

Miller, C.A., work in progress. Ph.D. dissertation.

Sullivan, G.E., 1991. Chemical evolution of basalts from 23 degrees N along the mid-Atlantic ridge: evidence from melt inclusions. Contributions to Mineralogy and Petrology, 296-308.

Treiman, A. H., 1992. The parent magma of the Nakhla (SNC) meteorite, inferred from magmatic inclusions. Geochemica et Cosmochimica Acta, 57, 4753-4767.

Thompson, R.N., 1974. Some high-pressure pyroxenes. Mineralogical Magazine, 39, 768-87.

Unkefer, J., 1992. Ascent rates of the Egersund Dikes. Senior These for the partial fulfillment of the requirements of a degree of bachelor of science in geology at Ohio State University (unpublished).

Venhuis, G.J. and Barton, M., Major element chemistry of Precambrian dolerite dikes of tholeiitic composition from Rogaland/Vest Agder, SW Norway. Nor. Geol. Tidsskr., 66, 277-294.

Walker, D., Shibata, T., and DeLong, S.E., 1979. Abyssal tholeiites from the oceanographer fracture zone. Contributions to Mineral. Petrol.,70,111-125.

Watson, E.B., 1976. Glass inclusions as samples of early magmatic liquid: determinative method and application to a south Atlantic basalt. Journal of Volcanology and Geothermal Research, 1 (1976), 73-84.

Figure Explanations

Figure 1 Map of Rogerland/Adger SW Norway.

Figure 2 Bulk rock composition of the Egersund Dolerites plotted on the graph Na_2O+K_2O Vs. SiO_2 .

Figure 3 The trend of evolution for glass formation of data obtained from experiments at 1 Atm, and the zone for experiments at 8-10 kb. This data is plotted on a Di-Ol-Sil pseudoternary. The chilled margin bulk compositions are also plotted.

Figure 4 Bulk rock compositions of olivine tholeiites and tholeiites on the Di-Ol-Sil pseudoternary.

Figure 5 Experiments with pyroxene at a range of pressures plotted as P (kb) vs Al^{VI} /AL^{IV} Gap between 1 Atm and 6-8 kb represents a lack of experimental data.

Figure 6 Groundmass, gabbro xenolith, and melt inclusion pyroxene Al^{VI} and Al^{IV} abundance calculated assuming six oxygens. Lines represent ratios of 1:1, 1:2, and 1:4.

Figure 7 Trends in Anorthite content over a range of pressures for several different starting compositions.

Figure 8 Anorthite content of the rims and cores of plagioclase phenocrysts in the Egersund Dolerite.

Figure 9 Albite-anorthite-orthoclase content of groundmass and melt inclusion feldspar.

Figure 10 Continental flood basalt bulk composition from a number of provinces plotted on the Di-Ol-Sil pseudoternary.

Figure 11 Kaersutite composition from the SNCs and other terrestrial sources.

Figure 12 plot of Al^{VI} /Al^{IV} in pyroxenes from the SNCs and the Egersund Dolerites.

Figure 13 Bulk rock compositions of the nakhlite, shergottite, and chassigny meteorites plotted on the Di-Ol-Sil pseudoternary.

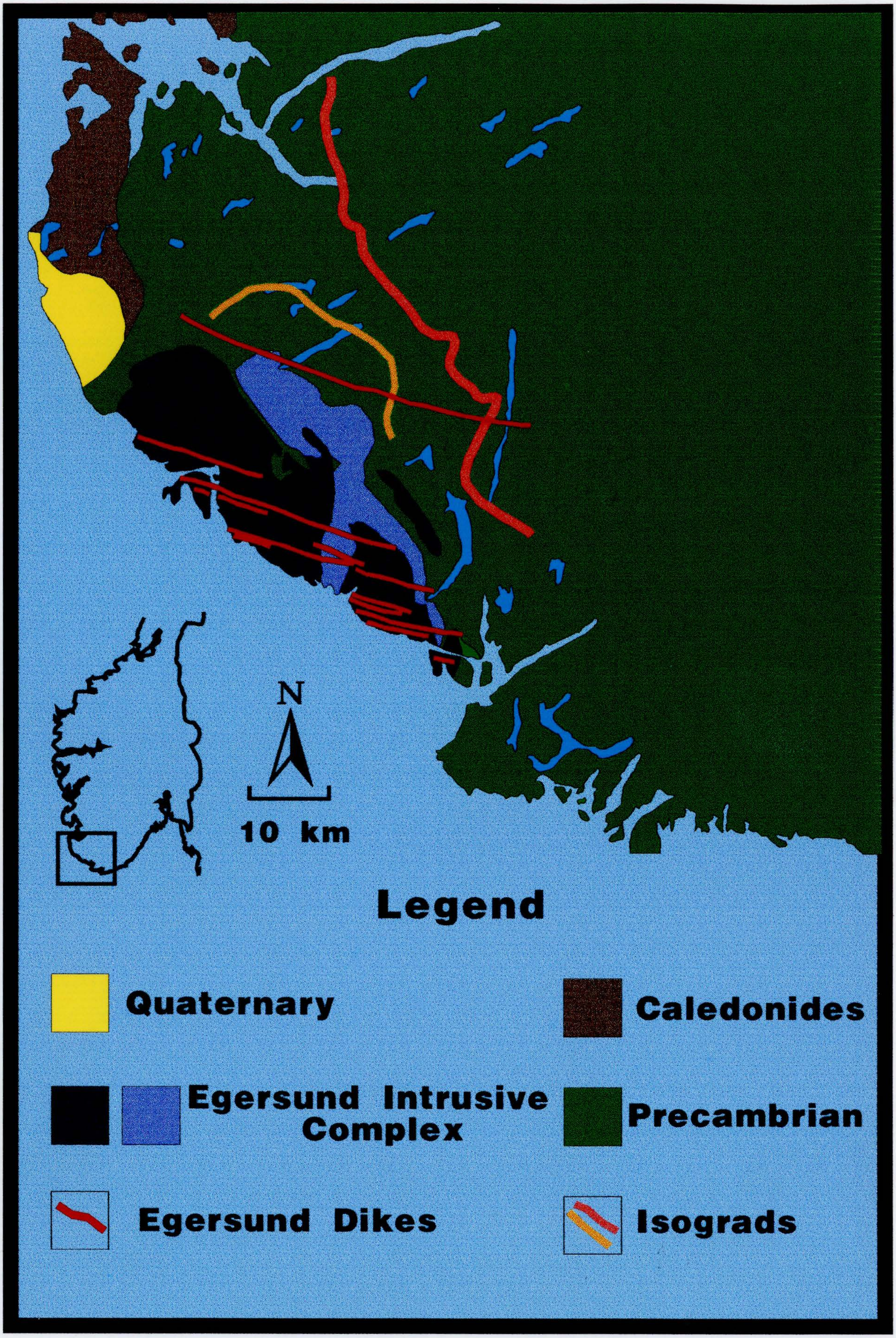
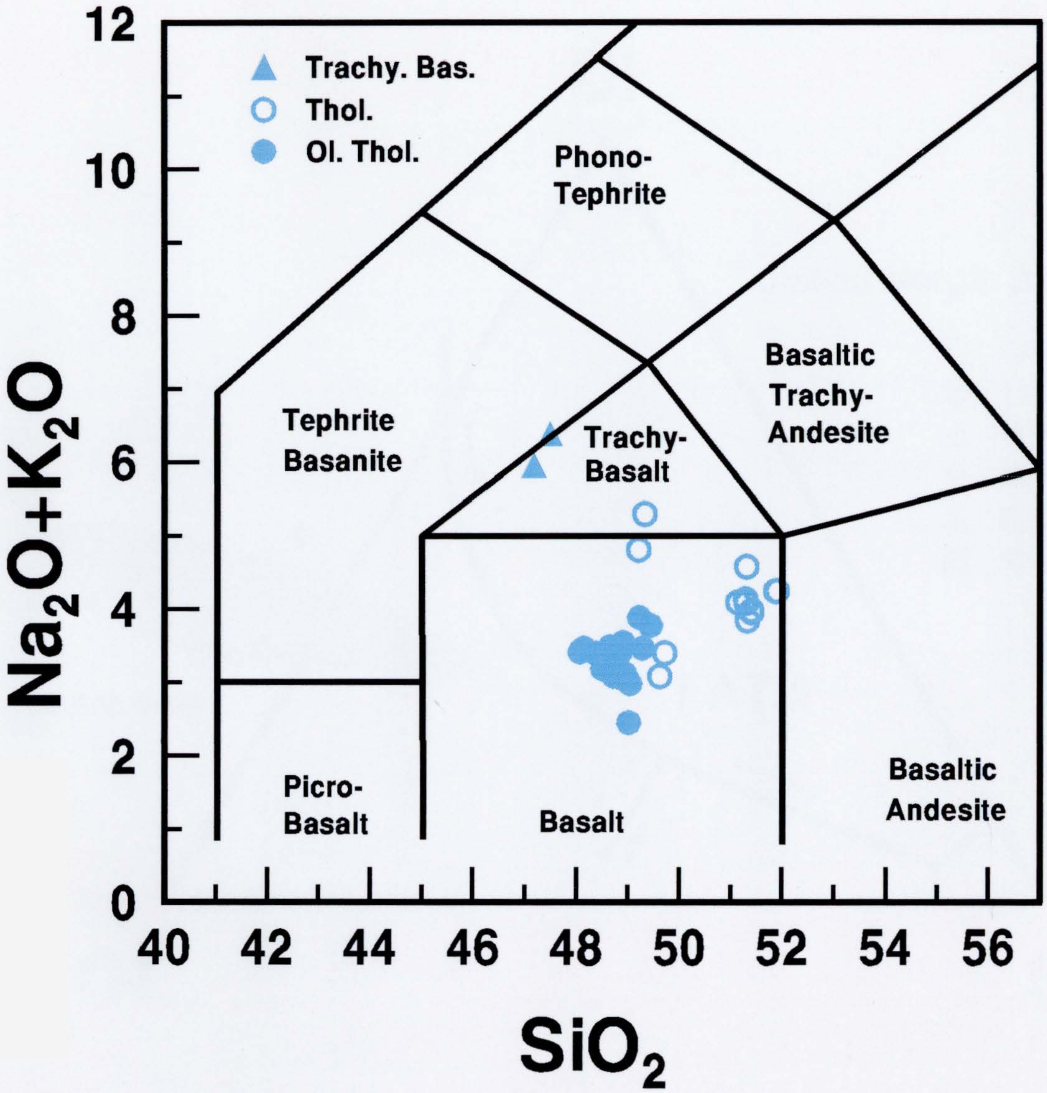

N
10 km
Legend
Quaternary
Caledonides
Egersund Intrusive Complex
Precambrian
Egersund Dikes
Isograds

Figure 1

Figure 2



Trachy. Bas.
Thol.
Ol. Thol.
Phono-
Tephrite
Tephrite
Basanite
Trachy-
Basalt
Basaltic
Trachy-
Andesite
Picro-
Basalt
Basalt
Basaltic
Andesite
0
2
4
6
8
10
12
40
42
44
46
48
50
52
54
56
Na_2O+K_2O
SiO_2

Fig. 3

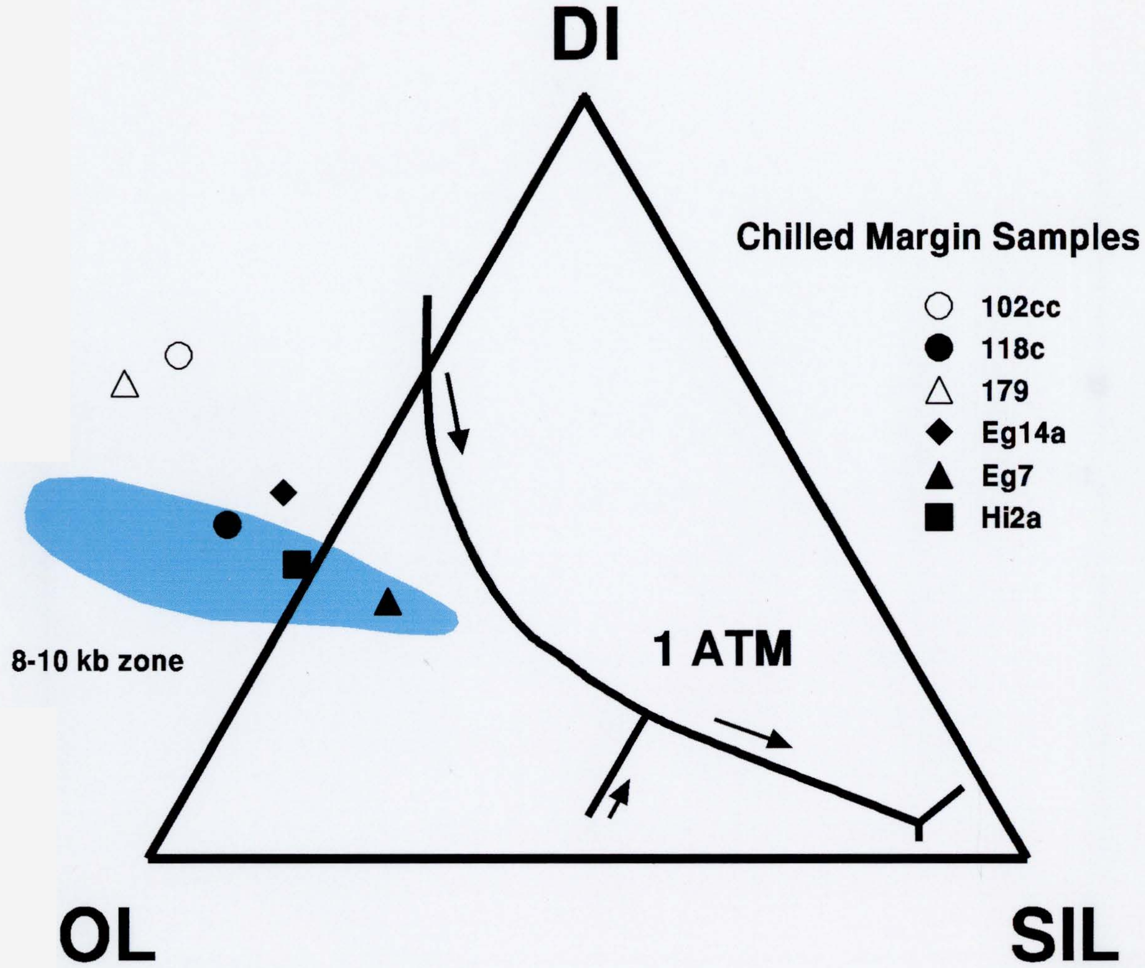
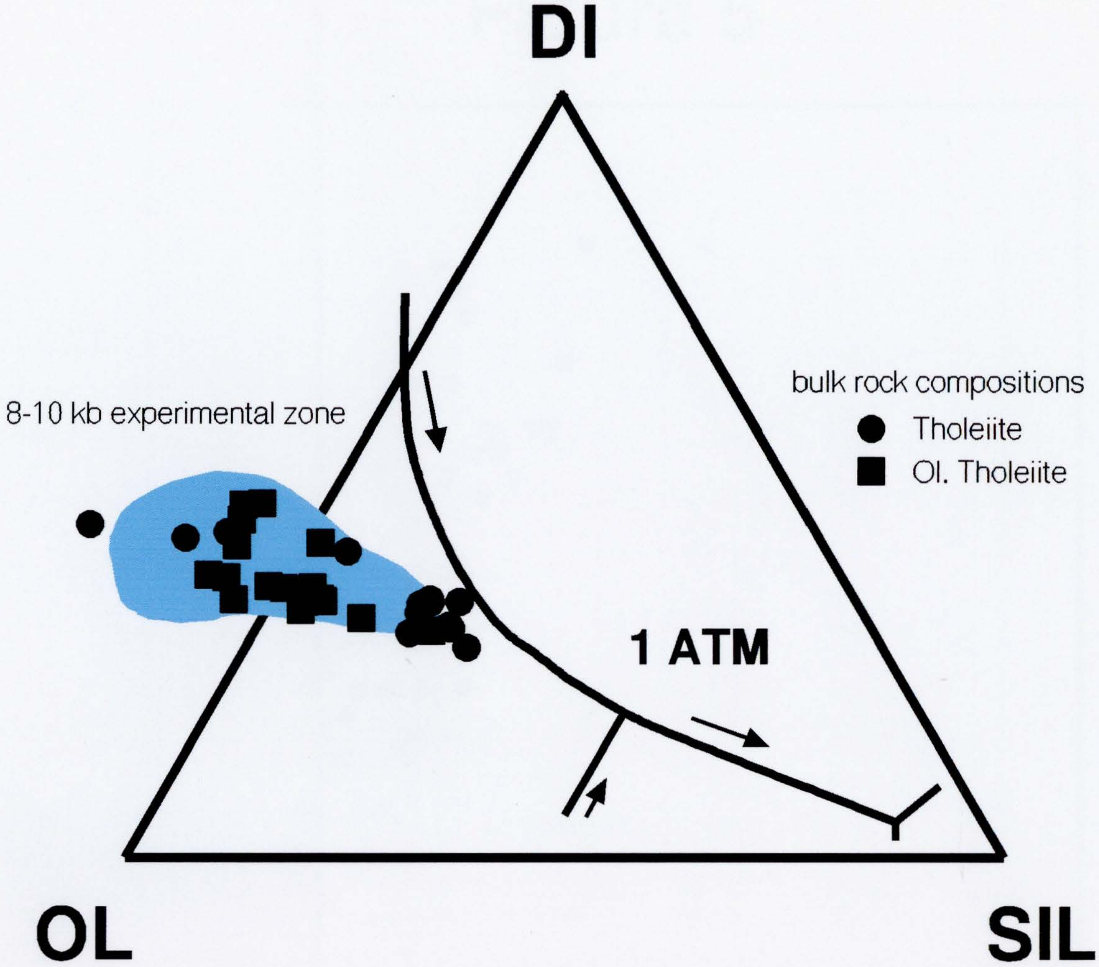

DI
Chilled Margin Samples
102cc
118c
179
Eg14a
Eg7
Hi2a
8-10 kb zone
1 ATM
OL
SIL

Figure 4



DI
8-10 kb experimental zone
bulk rock compositions
Tholeiite
Ol. Tholeiite
1 ATM
OL
SIL

Figure 5

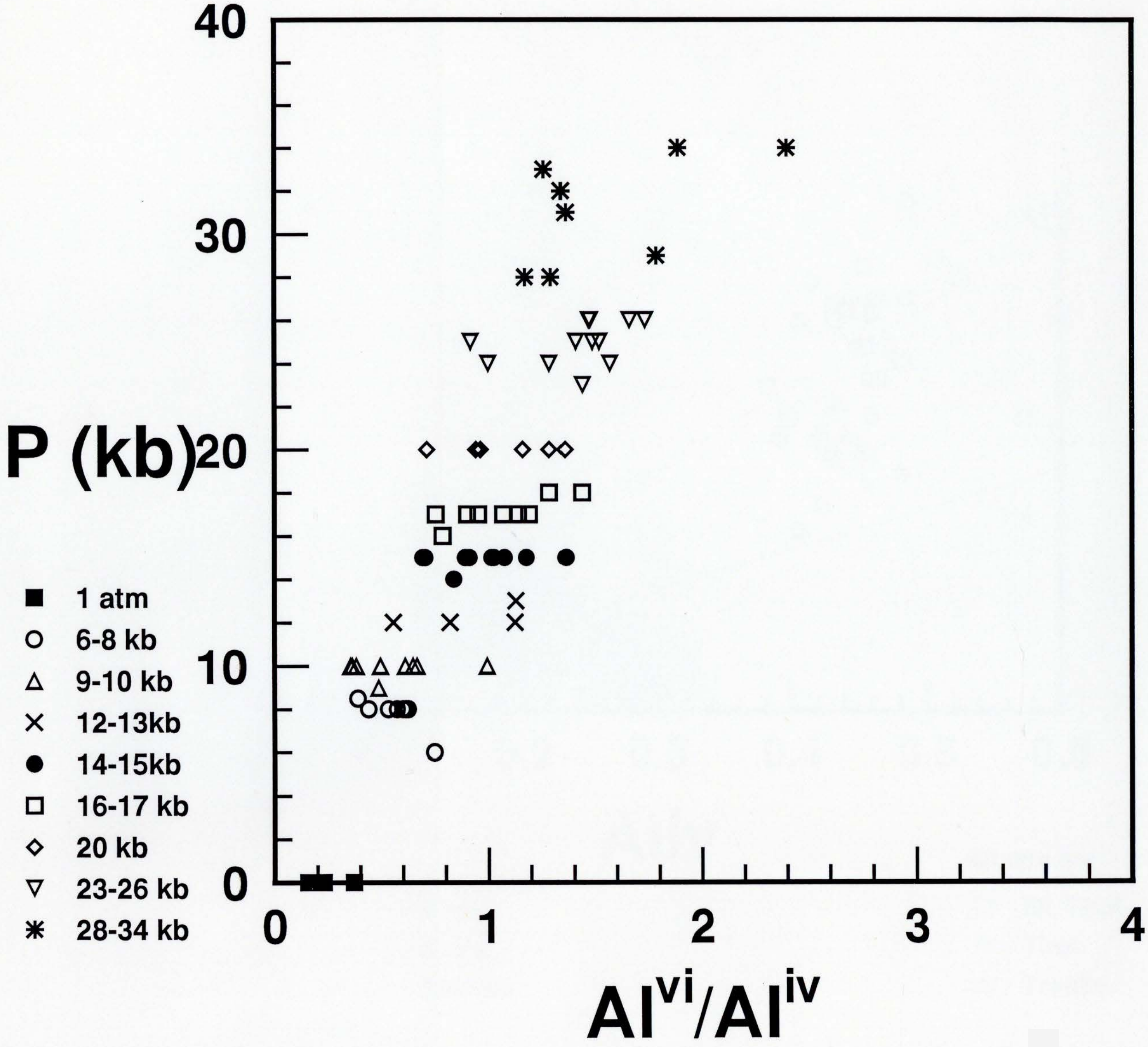

P (kb)
0
10
20
30
40
0
1
2
3
4
Al^{vi}/Al^{iv}
1 atm
6-8 kb
9-10 kb
12-13kb
14-15kb
16-17 kb
20 kb
23-26 kb
28-34 kb

Figure 6

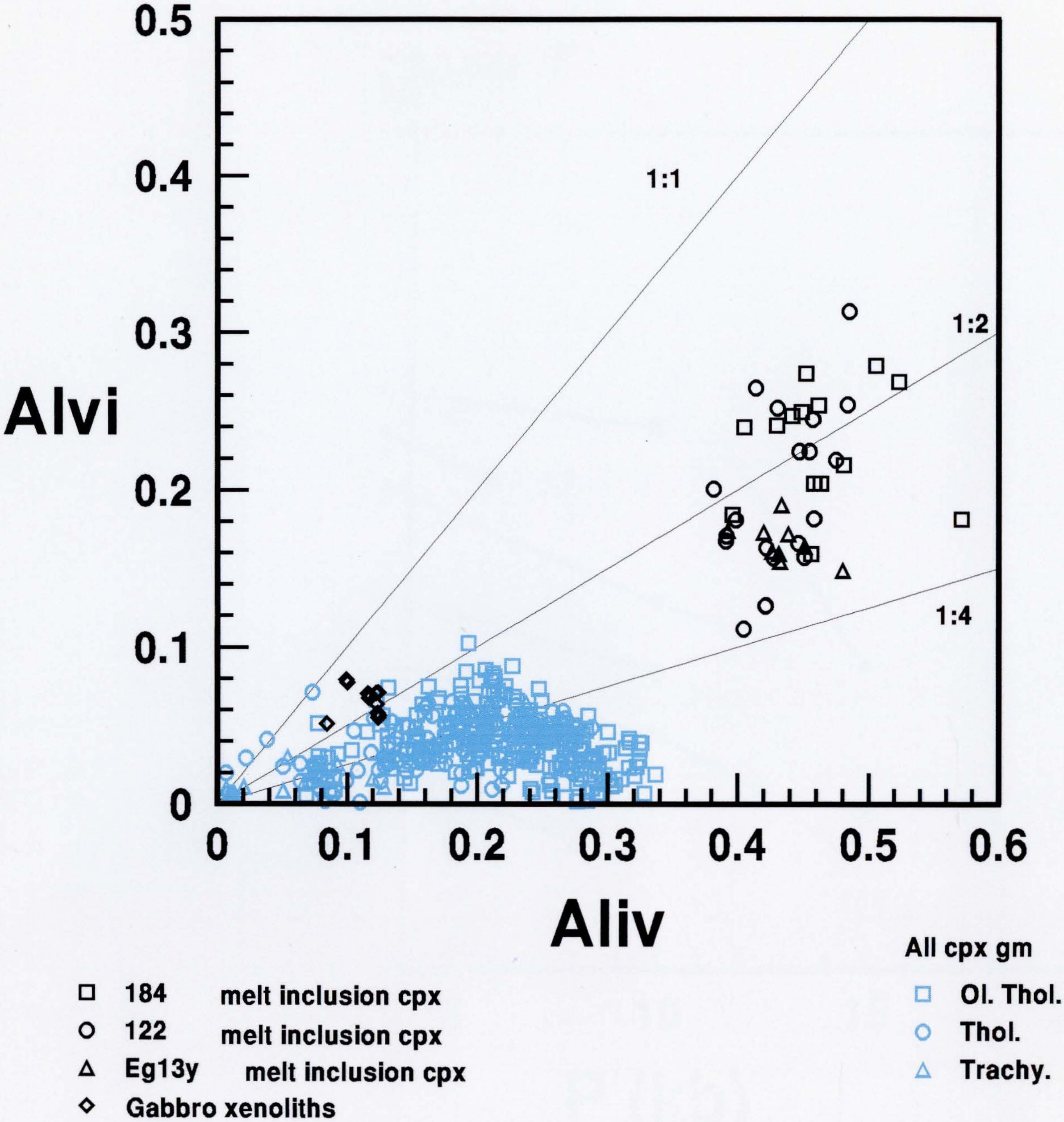
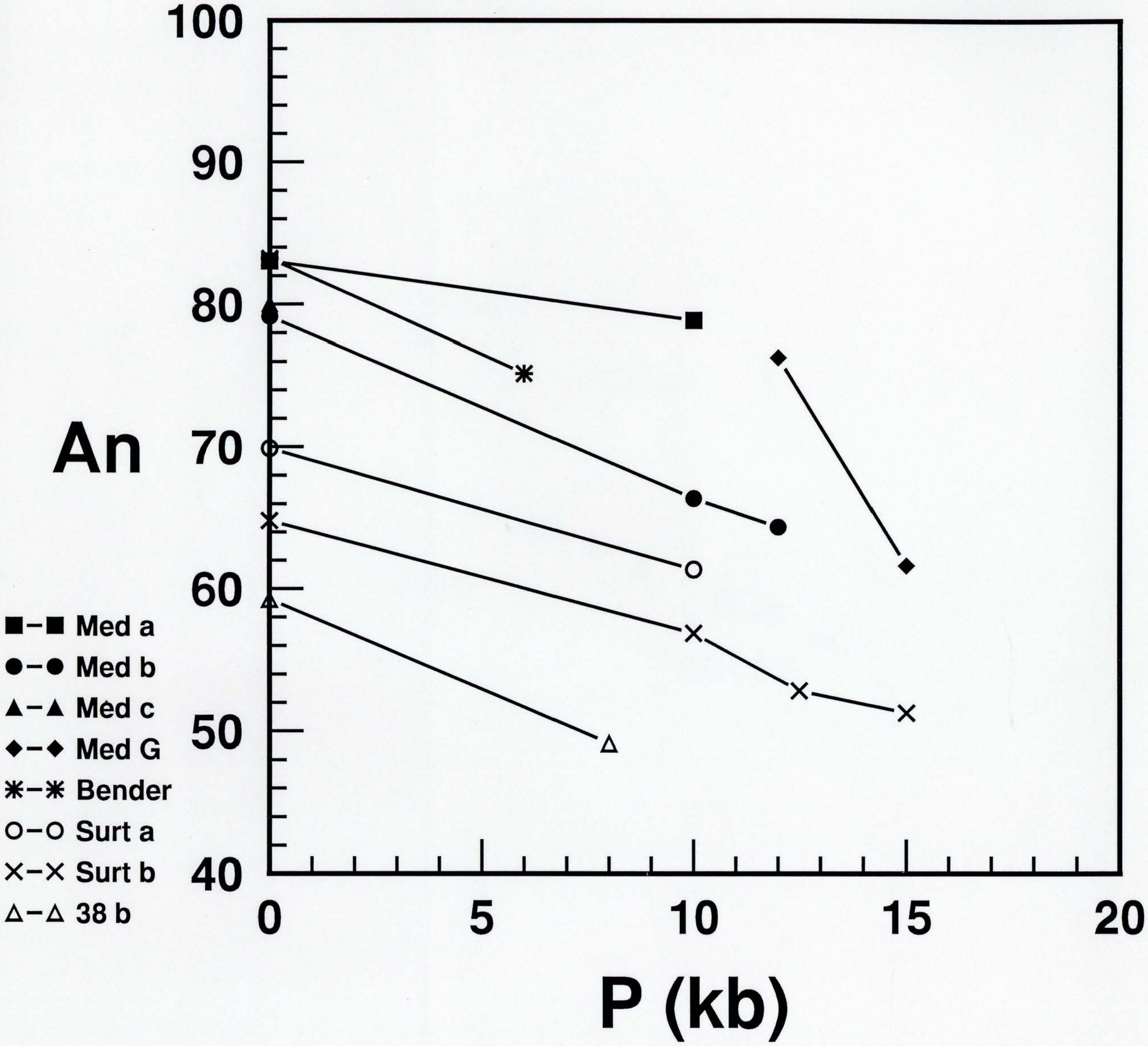
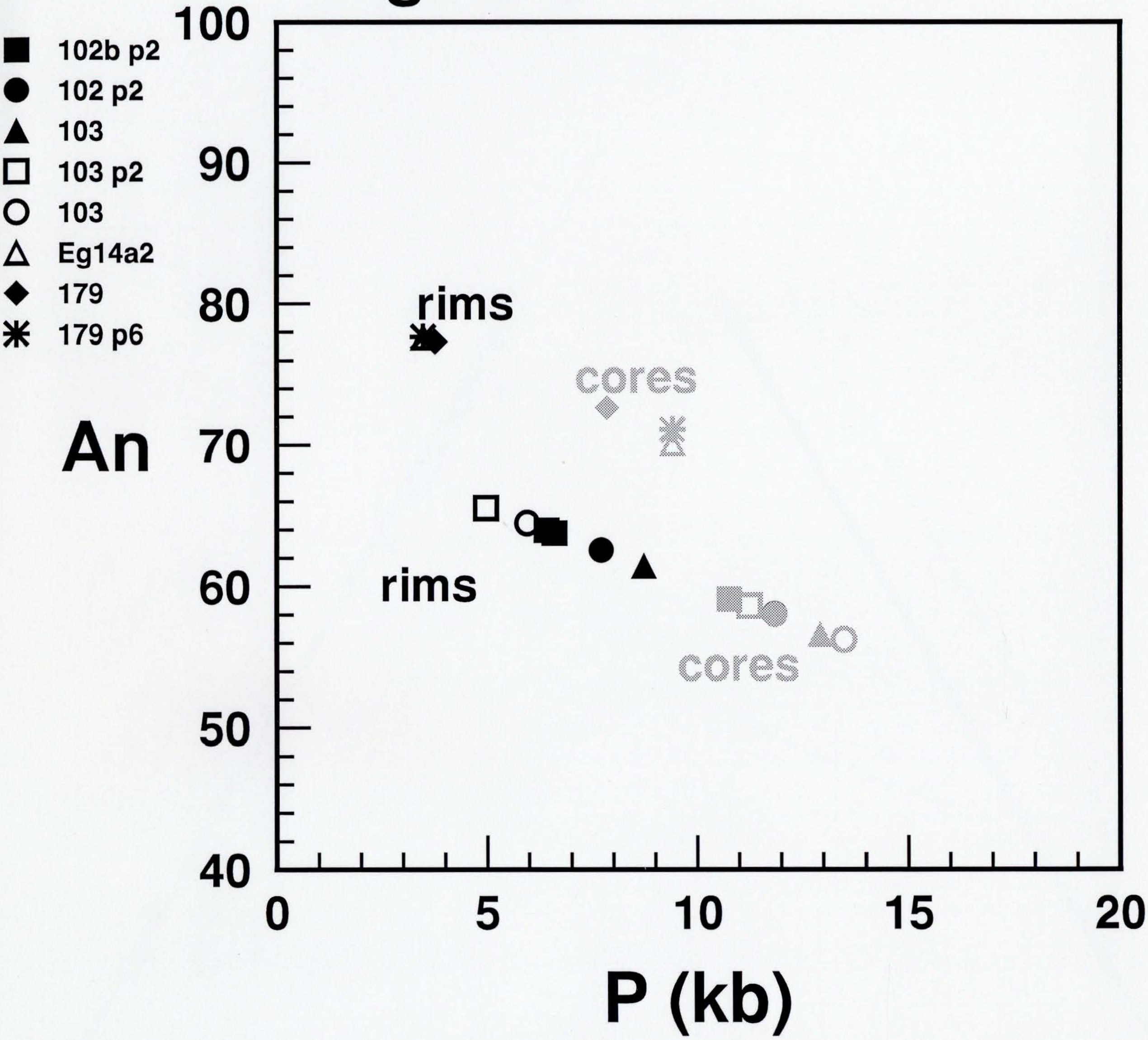

0.5
0.4
0.3
0.2
0.1
0
Alvi
1:1
1:2
1:4
0
0.1
0.2
0.3
0.4
0.5
0.6
Aliv
All cpx gm
184 melt inclusion cpx
122 melt inclusion cpx
Eg13y melt inclusion cpx
Gabbro xenoliths
Ol. Thol.
Thol.
Trachy.

Figure 7



100
90
80
70
60
50
40
An
0
5
10
15
20
P (kb)
Med a
Med b
Med c
Med G
Bender
Surt a
Surt b
38 b

Figure 8



Composition of the core and rim of several megacrysts

Figure 9

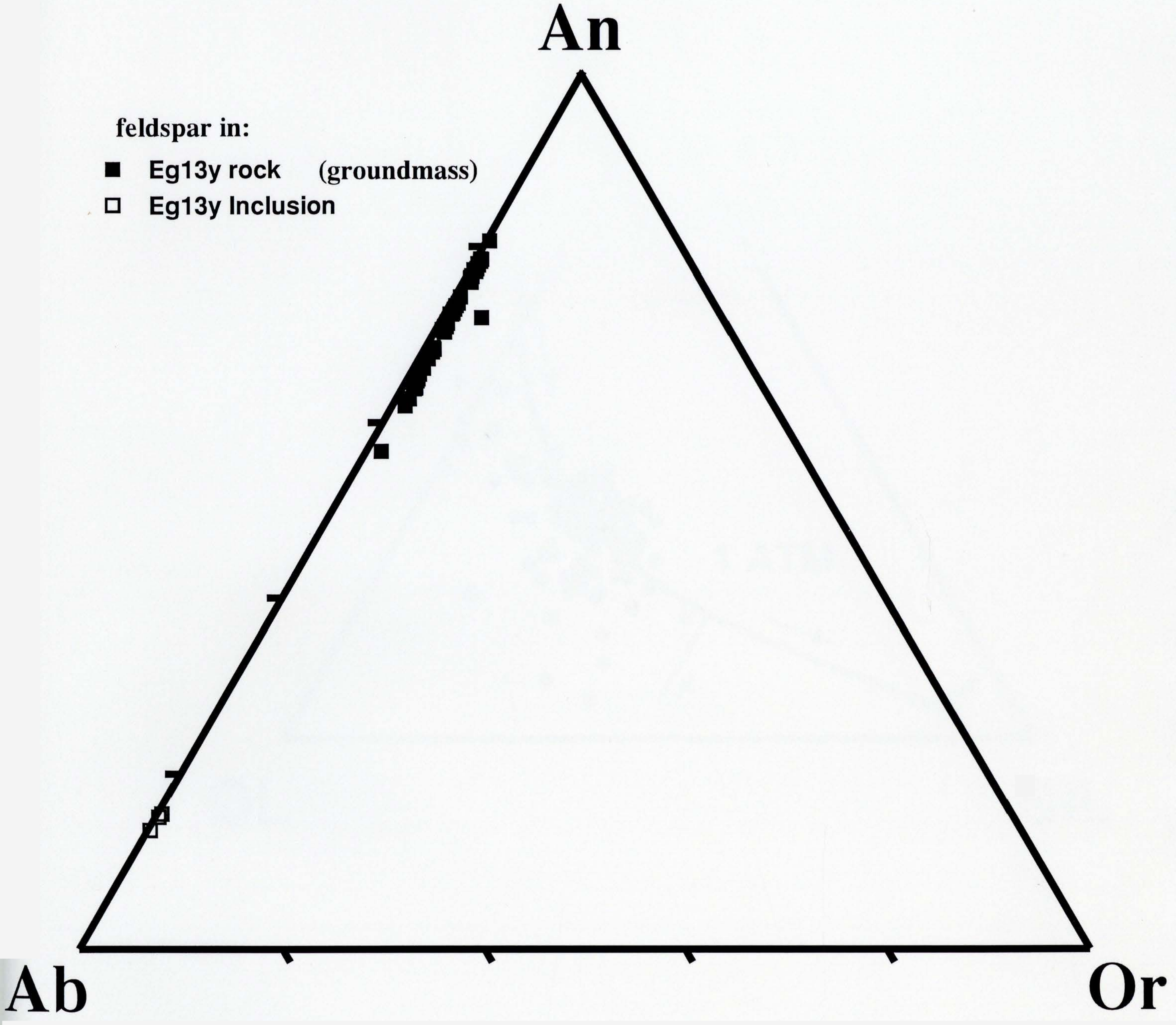


Figure 10

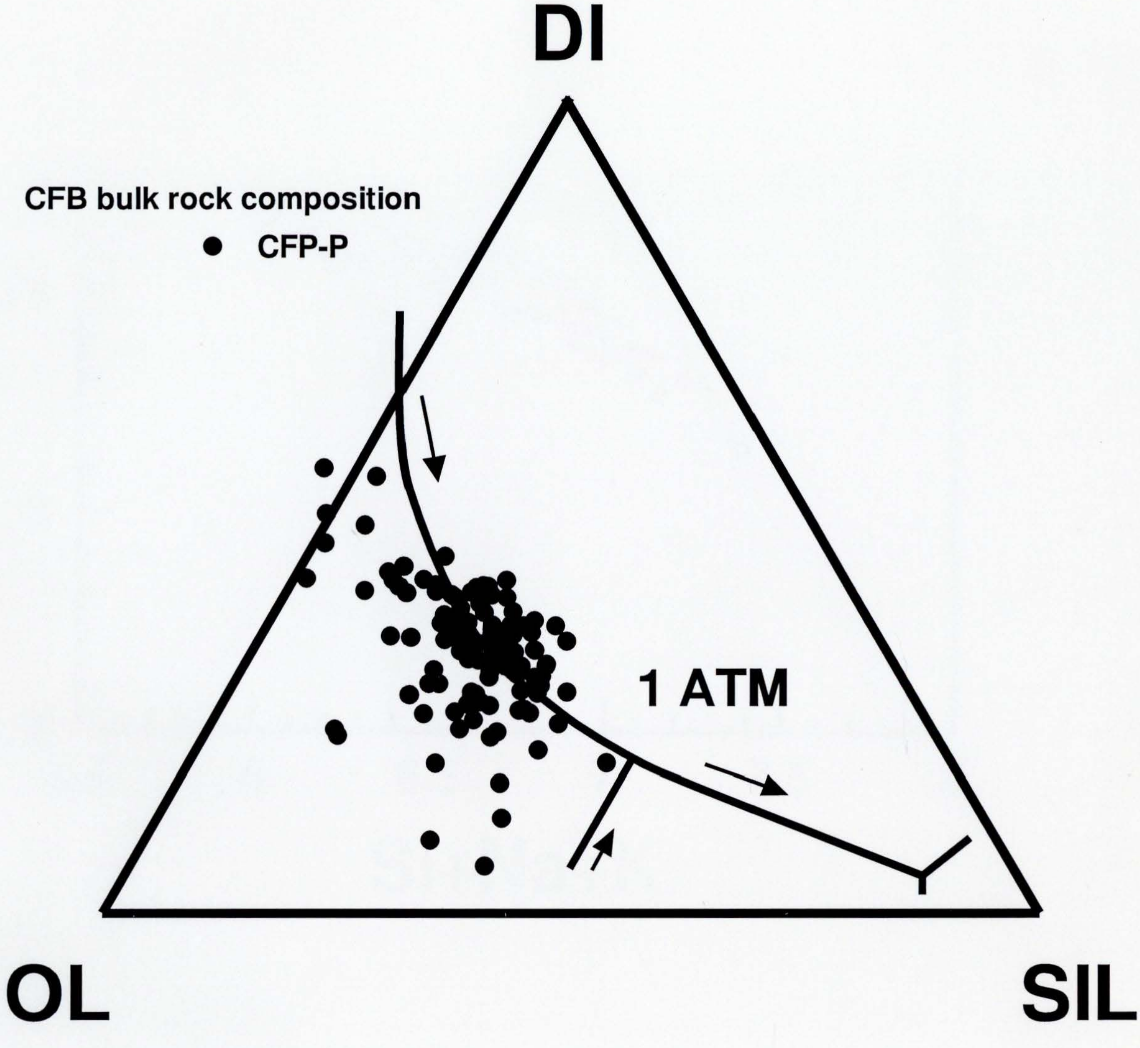


Figure 11

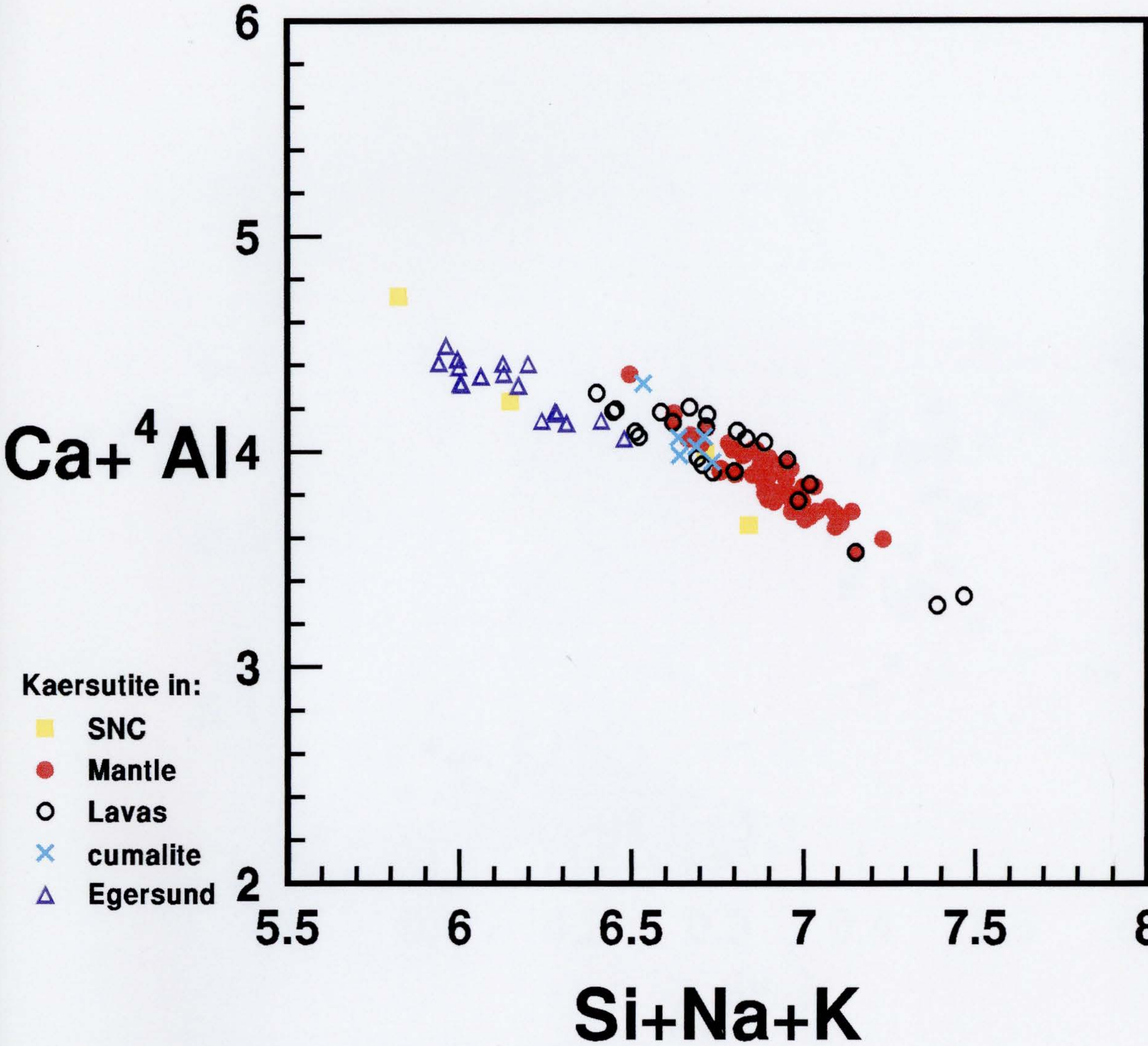
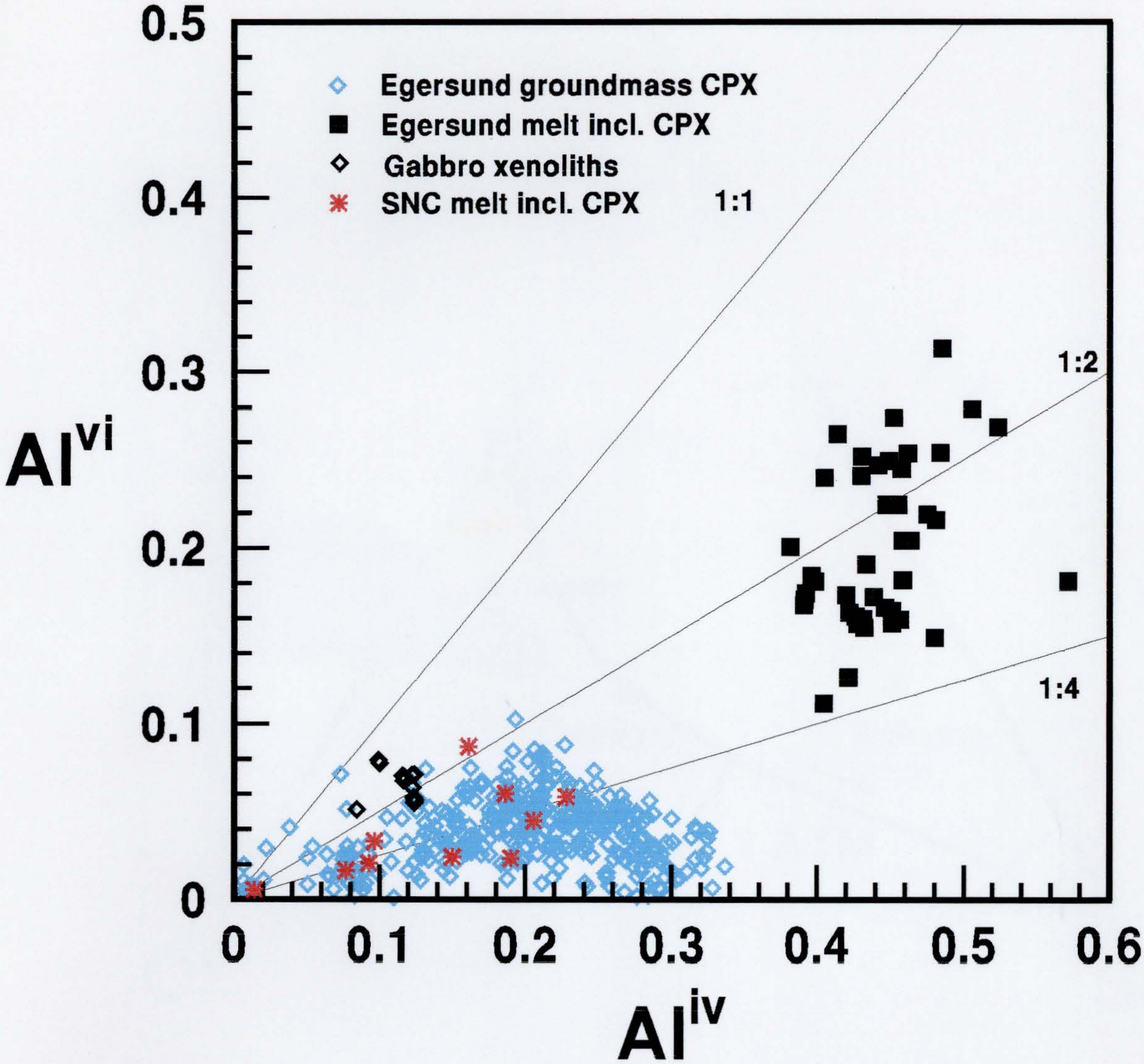
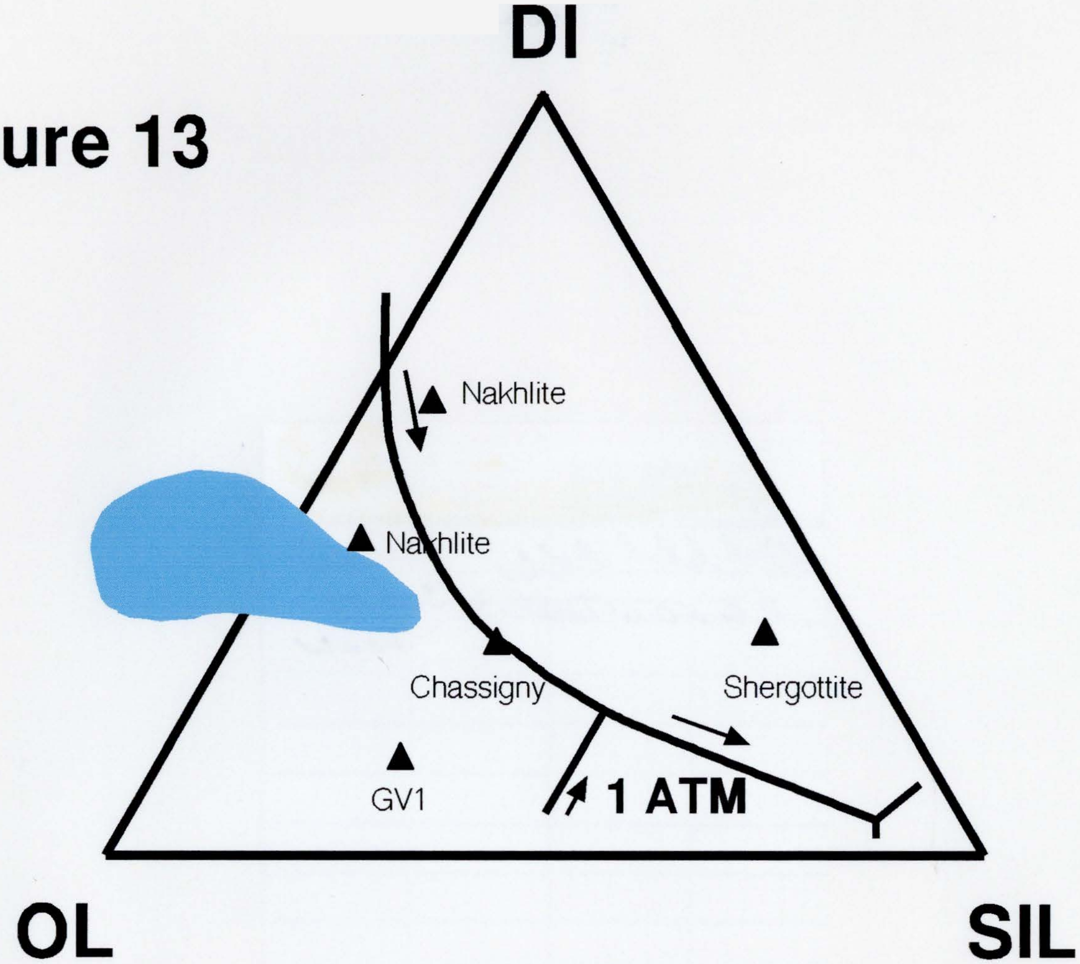

6
5
4
3
2
Ca+^{4}Al
5.5
6
6.5
7
7.5
8
Si+Na+K
Kaersutite in:
SNC
Mantle
Lavas
cumalite
Egersund

Figure 12



Egersund groundmass CPX
Egersund melt incl. CPX
Gabbro xenoliths
SNC melt incl. CPX
1:1
1:2
1:4
0.5
0.4
0.3
0.2
0.1
0
Al^{vi}
0
0.1
0.2
0.3
0.4
0.5
0.6
Al^{iv}

Figure 13


DI
Nakhlite
Nakhlite
Chassigny
Shergottite
GV1
1 ATM
OL
SIL